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Developments in deep brain stimulation using time dependent magnetic fields

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The effect of head model complexity upon the strength of field in different brain regions for transcranial magnetic stimulation (TMS) has been investigated. Experimental measurements were used to verify the validity of magnetic field calculations and induced electric field calculations for three 3D human head models of varying complexity. Results show the inability for simplified head models to accurately determine the site of high fields that lead to neuronal stimulation and highlight the necessity for realistic head modeling for TMS applications. © *2012 American Institute of Physics*. [doi:10.1063/1.3676623]

I. INTRODUCTION

Transcranial magnetic stimulation (TMS) is an established diagnostic and investigatory technique capable of activating neurons in the brain noninvasively.[1] Increasingly, TMS is showing promise for therapeutic purposes, but new applications are limited due to the rapid decrease of field intensity as a function of distance from the coils.[2,3] The ability to accurately target a specified brain region and to stimulate brain tissue at depth would allow new applications of the technique to be developed, which would replace invasive methods currently used to achieve these objectives. Attempts to improve the performance of TMS have been made by changing the coil design[4] as well as modifying the pulse shape[5] and current waveform.[6] In order to improve the design of TMS stimulator coils, the ability to accurately predict the site of stimulation within the human brain is necessary.

Previous investigations[7] have shown tissue heterogeneity and anisotropy of electrical conductivity can have a significant effect upon induced electric field. By directly comparing homogeneous and heterogeneous head models, the extent to which tissue heterogeneity affects the induced electric field in the brain can be assessed and the importance of realistic head modeling evaluated.

II. DETAILS OF THEORETICAL AND EXPERIMENTAL ANALYSIS

Calculations of magnetic and electric field have been performed using SEMCAD X electromagnetic modeling software with three 3D human head models of varying complexity. The simplest model comprises of a homogeneous sphere with radius of 100 mm. Two further models are shown in Fig. 1; the homogeneous standard anthropomorphic model (SAM) and a realistic, heterogeneous head model obtained from MRI data of a 34-year-old adult male. The realistic model allows for values of relative permittivity and electrical conductivity to be applied independently for each structure within the head. This capability is important as grey matter has an electrical conductivity an order of magnitude less than the cerebral-spinal fluid which surrounds it, whereas a simplified head model would apply a single averaged value throughout. Values of dielectric properties used for the main tissue regions are shown in Table I.

The method for solving the magnetic and electric fields implements a low frequency solver based on a quasi-static model, assuming zero Neumann boundary conditions and requiring current sources to be external to the lossy computational domain.

Each model incorporated a sinusoidal magnetic flux density of 2.5 kHz and a current of 5 kA in the modeled coil with a solution domain resolution of 0.1 mm. The spherical and SAM homogeneous human head models were specified as having electrical conductivity, relative permeability, and relative permittivity of 0.33 S/m, 1.0, and 11 000, respectively. In each case, the coil was modeled as being placed directly over the vertex of the head models.

To ensure that valid calculations of electric field were obtained, magnetic field measurements were performed using a gaussmeter and axial probe with an active area of 0.46 mm^2 positioned by a multi-axis linear stage system with an accuracy of 0.6 μm/μm. The magnetic field measurements were taken for a "figure-of-eight" type[8] Magstim Double

TABLE I. Values of dielectric properties used for heterogeneous head model.

Tissue	Permittivity	Elec. Cond. (S/m)
Brain (grey matter)	7.81×10^4	1.04×10^{-1}
Brain (white matter)	3.43×10^4	6.45×10^{-2}
Cerebellum	7.84×10^4	1.24×10^{-1}
Cerebrospinal fluid	1.09×10^2	2.00
Skin	1.14×10^3	2.00×10^{-4}
Skull	1.44×10^3	2.03×10^{-2}

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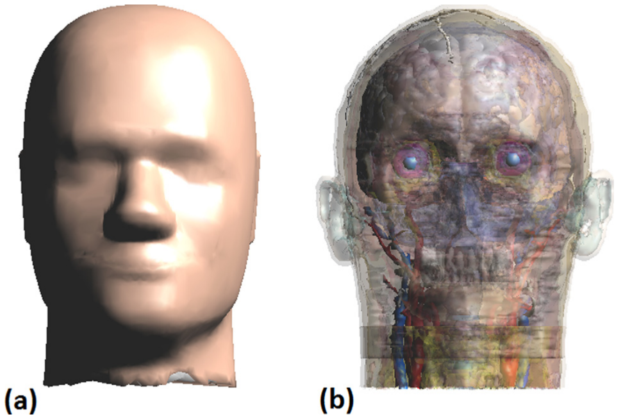

FIG. 1. (Color online) (a) Homogeneous standard anthropomorphic model and (b) heterogeneous MRI-derived human head model of an adult male.

70 mm remote control coil energized using a Magstim 200[2] stimulator at 100% output.

III. RESULTS AND DISCUSSION

Axial magnetic field measurements were taken across the x-axis of the Magstim Double 70 mm remote control coil at a distance of 20 and 50 mm (z-axis) as shown in Fig. 2. The figure shows that the greatest field intensity is present at the center of both coil windings, reaching approximately 0.5 MA/m at a distance of 20 mm and 0.15 MA/m at a distance of 50 mm.

A typical distance between the scalp and the cortical surface is 14.3 mm.[9] In this investigation, we focus on field profiles at a distance of 20 mm from the plane of the coil, a distance at which neuronal activation is feasible and 50 mm, a depth at which it is unlikely that stimulation can currently be achieved non-invasively.

The geometry and number of turns in the Magstim Double 70 mm remote control coil was established and modeled for use in electromagnetic modeling software. Fig. 3 shows the calculated axial component of the magnetic field produced by this modeled coil at a distance of 20 mm (z-axis) from the coil plane.

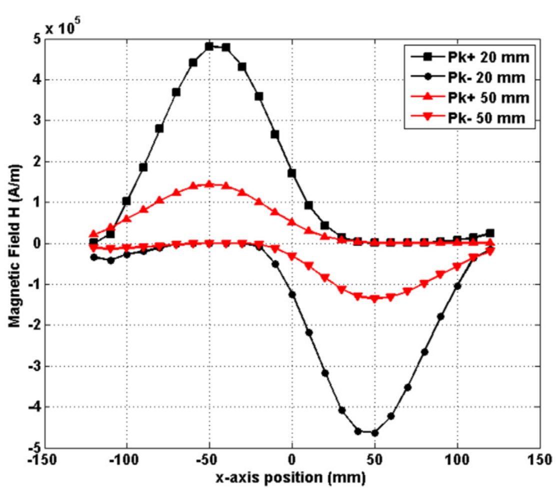

FIG. 2. (Color online) Measured axial magnetic field in plane 20 mm and 50 mm from the Magstim Double 70 mm remote control coil at 100% output.

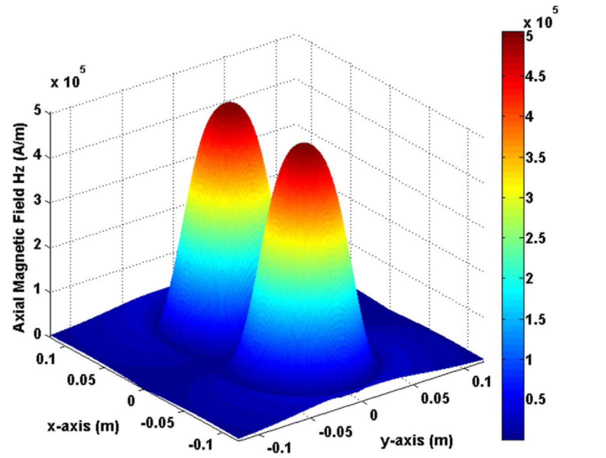

FIG. 3. (Color online) Calculated axial magnetic field in plane 20 mm from the coil surface.

As the results of the measured and calculated magnetic field show good agreement, the calculated electric field values can be assumed to be valid. The time dependent magnetic field produced by the TMS stimulator coil induces an electric field inside the head. If the electric field is of sufficient magnitude, an action potential is created, and neuronal activation is achieved. For this reason, we use the calculated induced electric field to determine where neuronal activation is likely to occur.

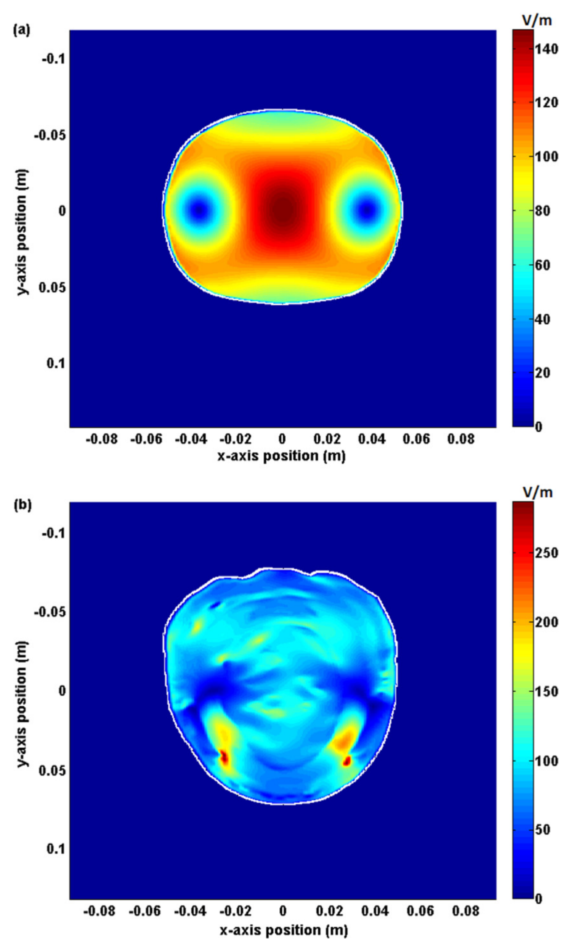

FIG. 4. (Color online) (a) Calculated electric field in homogeneous and (b) realistic human head model in plane 20 mm from the coil surface.

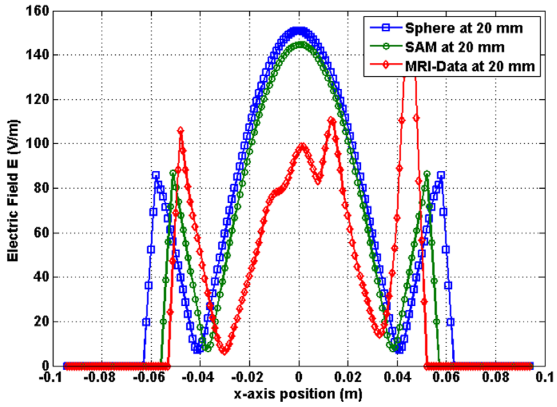

FIG. 5. (Color online) Calculated electric field profile 20 mm from coil surface for three human head models.

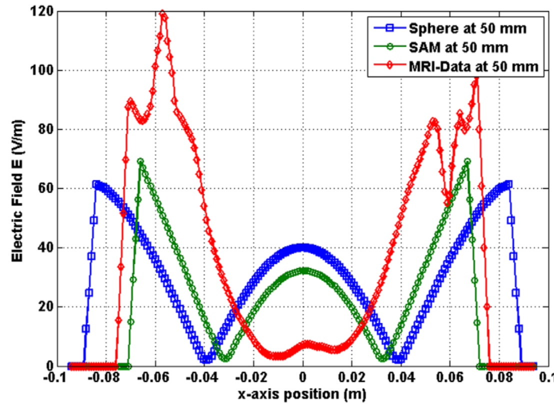

FIG. 6. (Color online) Calculated electric field profile 50 mm from coil surface for three human head models.

The electric field required to achieve neuronal stimulation typically occurs between 30 and 100 V/m,[10] although this can vary depending on direction. The calculated electric field in the plane 20 mm from the 70 mm double coil for the homogeneous SAM and heterogeneous MRI-derived head model is shown in Fig. 4.

The calculated electric field in each human head model at a distance of 20 mm from the coil surface is shown in Fig. 5. It is expected that the maximum field intensity will be directly beneath the center of the coil at $x = 0$. The magnitude of electric field for the heterogeneous head model in this region is approximately 70% of that calculated for the two homogeneous models. Conversely, the peaks at ± 50 mm are greater for the heterogeneous head model than the two homogeneous head models, indicating that field intensity closer to the surface of the head is greater than that determined with a homogeneous head model.

Calculated electric field 50 mm from coil surface for each human head model is shown in Fig. 6. Here it is demonstrated that use of the simplified homogeneous human head models may erroneously lead to the prediction of stimulation below the vertex at a depth of 50 mm using a 70 mm double coil, due to the magnitude of electric field exceeding 30 V/m. The realistic heterogeneous head model indicates the value of induced electric field in this region is likely to be well below the field required to generate an action potential. In contrast, the field seen closer to the surface of the head at this distance from the coil is greatly increased, giving rise to the possibility of having two stimulated sites with a spatial separation of 100 mm.

IV. CONCLUSION

Experimental measurements and theoretical calculations have been performed to assess the impact of human head model complexity upon the calculation of electric field in the brain for neuronal activation. It has been shown that tissue heterogeneity has a significant effect on the distribution of electric field and that in general a simplified head model will underestimate the field intensity at the surface of the head and overestimates the field intensity at depth in the brain.

As the physical characteristics of the brain will vary for each TMS patient, the spatial variation of the induced electric field will change. The consequence of this is that a TMS coil may not be able to accurately stimulate the same brain region for different patients. The necessity to implement realistic head modeling for assessing coil designs for noninvasive deep brain stimulation has also been demonstrated.

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